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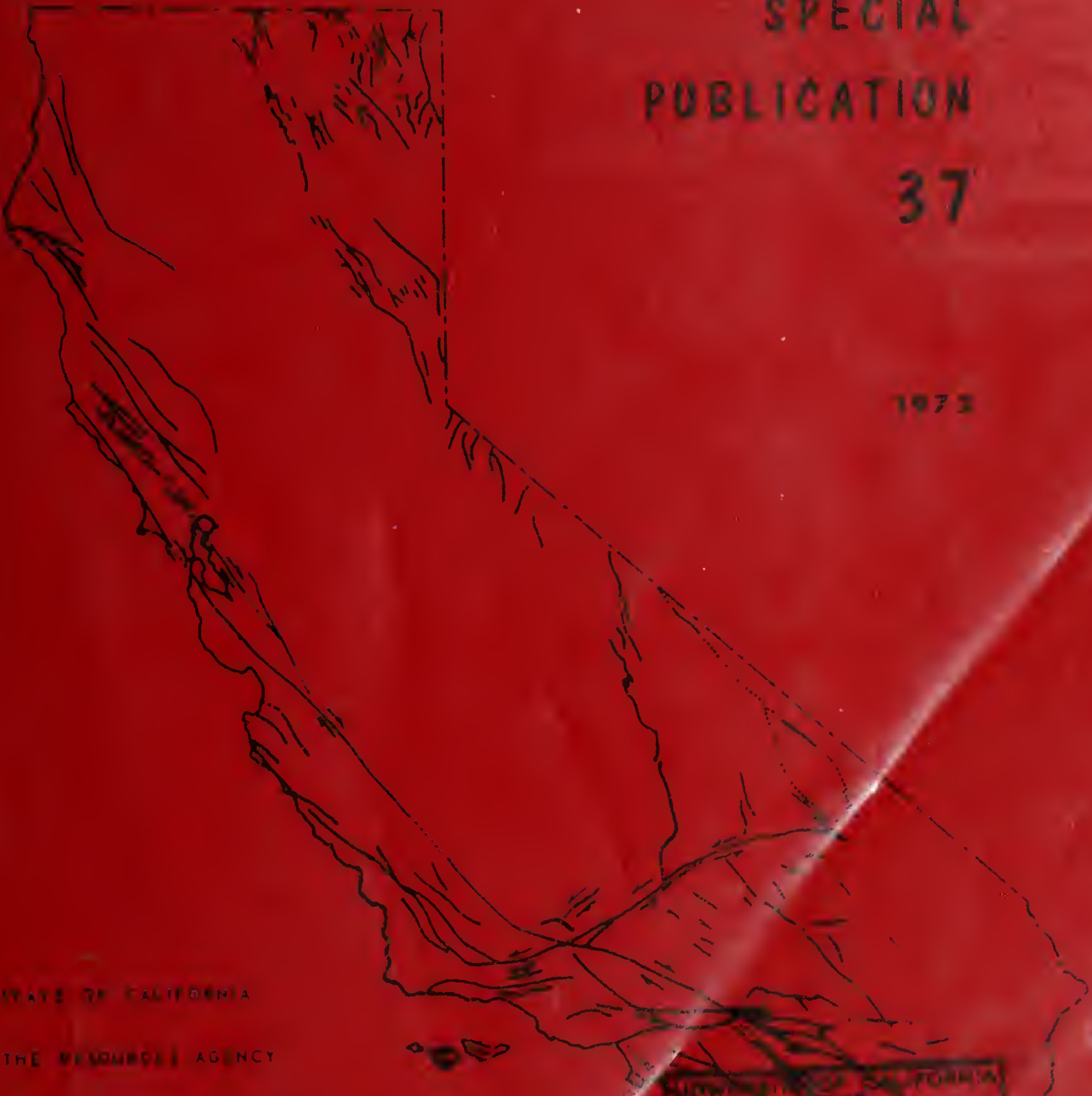
CRUSTAL MOVEMENT INVESTIGATIONS

SPECIAL PUBLICATION 37

1973



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Crustal Movement Investigations In California: Their history, data, and significance

BY ROGER W. GREENSFELDER
Seismologist, California Division of Mines and Geology
Sacramento, California
1972

This report reviews crustal movement studies in California and provides background information for the accompanying map, "Locations of crustal movement investigations in California". The map and accompanying index were prepared in recognition of a vital need--on the part of earth scientists, engineers, and others--for a timely summary of the operational progress of crustal movement studies in this state. Earth scientists directly involved in such studies need to be cognizant of similar work being carried out by their colleagues to prevent duplication of effort and to assure maximum utilization of all available data. This is especially important now, when a number of organizations are actively engaged in major field investigations.

Civil and structural engineers in California are aware of the hazard that fault movement poses to structures and, in the interest of public safety, need to have access to all available information concerning this subject. Advisors to federal, state, and local government officials involved in land-use planning or land management need information on fault movement, especially for planning and when considering zoning and building ordinances.

The map and accompanying tables show the locations, dates of installation, years and/or frequency of observation, responsible agencies, and instruments employed in the measurement of crustal deformation in California. Surveying methods used are: triangulation (geodetic and local), electro-optical distance ranging (including trilateration), alignment arrays, and leveling. Instruments used are: creepmeters, strain meters (extensometers), stress probes, and tiltmeters. See Glossary p. 21. Only those surveys specifically designed to study tectonic crustal movement are discussed in this paper. Intensive leveling is conducted in areas undergoing subsidence caused by fluid (oil or water) withdrawal; however, because subsidence is not a tectonic phenomenon, it is dealt with only briefly here.

In its most general sense, the term "crustal movement" includes short-period motions caused by the passage of seismic waves; however, this discussion is limited to crustal movements characterized by permanent and ultra-long-period (more than one year) deformation. Such deformation is not always closely associated with seismic energy release, but certainly interest in earthquake prediction is chiefly responsible for recently increased efforts to monitor crustal movement. In connection with earthquake prediction, the measurement of both long-term strain rates and short-term precursory strain events is important.

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Crustal Movement Investigations in California
by Roger W. Greensfelder

Page 4, paragraph 4: "figure 2" should be "figure 5".

Page 7, last line: "figure 3" should be "figure 2".

Page 10, paragraph 3, line 6: "figure 4" should be "figure 3".

Page 12, paragraph 1, line 6: "figure 5" should be "figure 4".

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Crustal movement occurs in two forms--*fault slip*, which may take place through both earthquake-generating rupture (brittle fracture) and aseismic plastic flow (creep), and *distortion* or *homogeneous strain* (simply referred to as *strain*), which may be distributed over a region many miles wide. Fault rupture apparently was first recognized in 1819 after the Cutch, India, earthquake. Since that time, surface faulting has been reported worldwide --most notably in western North America, Japan, New Zealand, and Turkey (Richter, 1958, p. 200-201). Creep and strain are more subtle than rupture and consequently were not recognized until more recently. The phenomenon of earth strain was first recognized by H. F. Reid (1910, p. 16-28) in his analysis of triangulation data in connection with the great 1906 San Francisco earthquake. Fault creep (though not called by that name) was first reported by T. W. Koch (1933) in connection with the active Buena Vista thrust fault, which had caused considerable damage to oil wells and pipelines.

Most historic surface faulting in North America has taken place in California and western Nevada (Bonilla, 1967). The first relatively well-documented occurrence in North America was in connection with the great Fort Tejon, California, earthquake of 1857, which was accompanied by surface rupture on a 225-mile-long (360 km) segment of the San Andreas fault between Cholame and San Bernardino (figure 1); right-lateral offset was perhaps as much as 10 m. Earlier earthquakes were, however, accompanied by ground breakage of an unspecified nature: in 1836 on the Hayward fault; in 1838 on the San Andreas fault, San Francisco peninsula; and in 1852 on the Big Pine fault. Since 1857, 19 occurrences of surface rupture have been reported in California (figure 1), the most recent being that which accompanied the San Fernando earthquake of 1971.

Geodetic triangulation after the 1906 San Francisco earthquake provided the first instrumental measurements of crustal displacements; and, until very recently, triangulation was the only instrumental method employed for that purpose. In the late 1950s, precise electro-optical distance ranging, at least ten times more accurate than triangulation, came into use; and it is only within the last six years that continuous recording of fault slip, strain, and tilt has been employed specifically to study the relationship between aseismic crustal movement and earthquakes. All of these techniques are discussed here.

Table 1. Tabulated list of historical earthquakes shown in figure 1.

Date and fault	Earthquake magnitude	Movement
1. 1836—Hayward fault	7.0 ± 0.5 (est.)	Ground breakage
2. 1838—San Andreas fault	7.0 ± 0.5 (est.)	Ground breakage
3. 1852—Big Pine fault	no data	Ground breakage
4. 1857—San Andreas fault	8.0 ± 0.5 (est.)	Right-lateral, possibly as much as 30′
5. 1861—Calaveras fault	no data	Ground breakage
6. 1868—Hayward fault	7.0 ± 0.5 (est.)	Strike slip
7. 1872—Owens Valley fault zone	8.3 ±	Down to E, 23′; right-lateral, 16′–20′, but some reports state left-lateral movement also occurred
8. 1899—San Jacinto fault	6.6 ± 0.42	Surface evidence questionable
9. 1901—San Andreas fault	6.3 ± 0.42	Ground breakage
10. 1906—San Andreas fault	8.3	Right-lateral, 21′
11. 1922—San Andreas fault	6.5	Ground breakage
12. 1934—San Andreas fault	6.0	Ground breakage
13. 1934—San Jacinto fault zone in Colorado River Delta	7.1	Distinct fault trace on 1935 aerial photographs
14. 1940—Imperial fault	7.1	Right-lateral, 19′
15. 1947—Manix fault	6.4	Left-lateral, 3″
16. 1950—Unnamed fault along west edge of Fort Sage Mountains	5.6	Down to W, 5″-8″
17. 1951—Superstition Hills fault	5.6	Right-lateral, slight
18. 1952—White Wolf fault	7.7	Reverse fault, south plate moved from SW to NE; left-lateral, 2′; throw 2′
19. 1956—San Miguel fault	6.8	Right-lateral, 3′; down to SW, 3′
20. 1966—Imperial fault	3.6	Right-lateral, 1½ cm
21. 1966—San Andreas fault	5.5	Right-lateral, several inches
22. 1968—Coyote Creek fault (San Jacinto fault zone)	6.5	Right-lateral, 33 cm.
23. 1971—San Fernando fault	6.6	Left-lateral,6′; reverse,6′

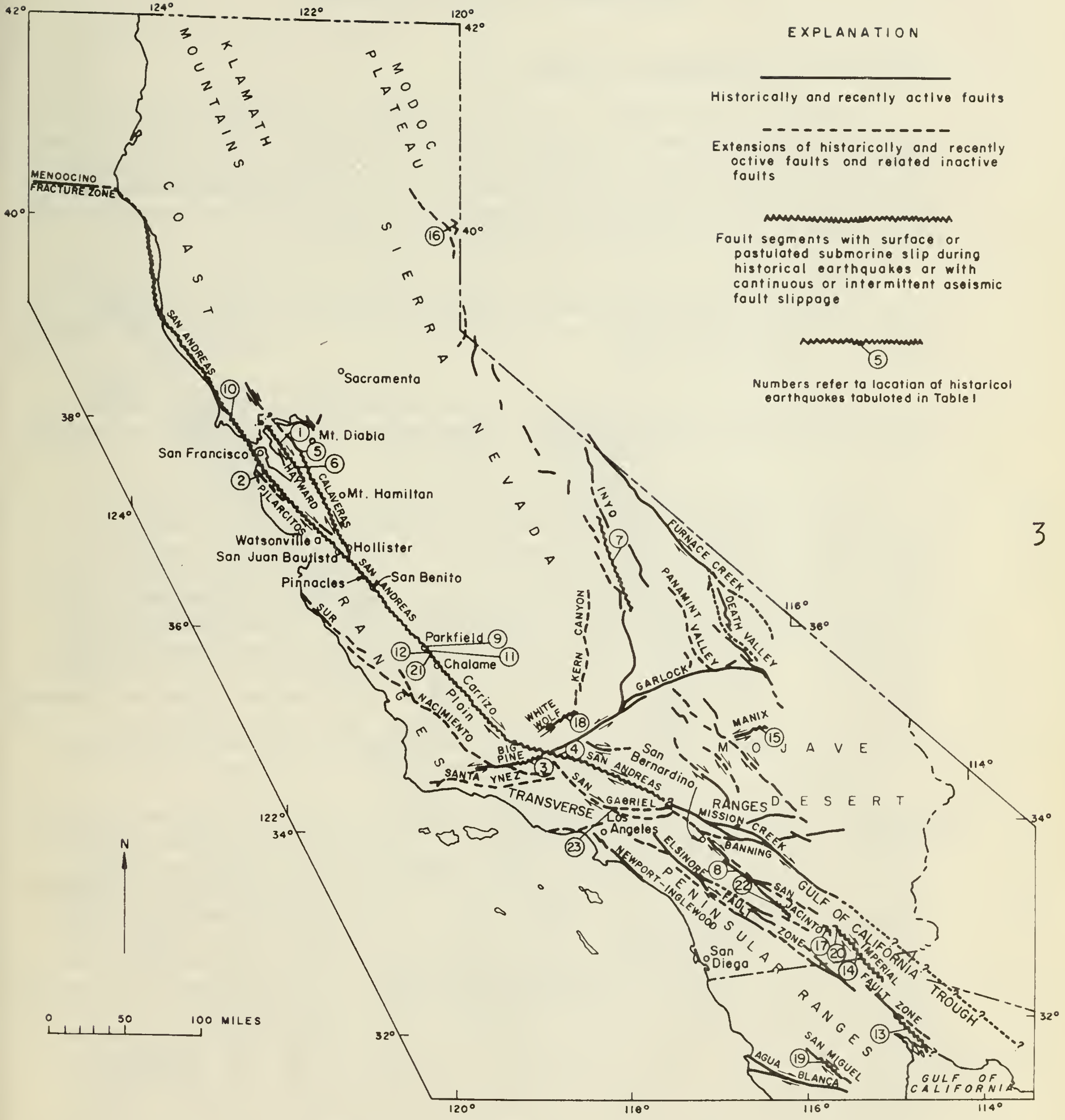


Figure I Surface faulting during historic earthquakes.

EARTHQUAKES AND CRUSTAL MOVEMENT

Accumulation and Release of Strain

According to the theory of elastic rebound, an earthquake results from the sudden release of accumulated strain energy. Elastic strain (see Glossary) builds up near a "locked" fault in the adjacent crustal blocks when they undergo relative displacement; when the accumulated strain is greater than the rock can sustain, the rock ruptures and the crustal block edges rebound past each other, releasing the strain.

Major strike-slip faults like the San Andreas are generally thought to be boundaries separating two differentially moving tectonic plates. In the case of the San Andreas fault, the oceanic plate is moving northwesterly past the continental plate.

Strain may be released in a noncatastrophic manner by fault creep. This form of strain release appears to be characteristic of the San Andreas fault between San Juan Bautista and Parkfield.

It is controversial whether fault slip due to creep and small earthquakes in the San Juan Bautista-to-Parkfield segment of the San Andreas fault system prevents accumulation of strain in that region. Clarence R. Allen (1968, p. 77) has hypothesized that strain release along five segments of the San Andreas fault system is characterized by one of two basic modes of seismic and creep behavior. One mode is characterized by frequent small-to-large earthquakes (up to Richter magnitude 7½) and creep and is common to the northern, central, and southern "active" areas (figure 2). The other mode is characterized by infrequent great earthquakes (Richter magnitude 8 and above), few small-to-large shocks, and no measurable creep and is common to the long segments that ruptured during the great 1857 Ft. Tejon and 1906 San Francisco earthquakes.

After analyzing geodimeter and triangulation data, Scholz and Fitch (1969, p. 6663) concluded that strain is accumulating everywhere along the San Andreas fault at a rate of about 1 ppm/yr and that creep and minor seismicity "do not release an appreciable amount of the accumulating strain and hence do not serve as a safety valve to prevent major earthquakes as Allen (1968) has suggested." In a later paper (1970), Scholz and Fitch found that the amount of creep *measured* on the San Andreas, Hayward, and Calaveras faults can account for only one-third of the changes in geodimeter line lengths in the region from the San Francisco Bay Area to San Benito; and, if no undetected creep is occurring, the principal strain rates must be about ½ ppm/yr. They then explored the possibility that *undetected* creep on minor faults can explain the geodimeter data. By postulating undetected creep at rates of 1.0 cm/yr on the Sargent and Silver Creek faults and 2.0 cm/yr on the Paicines fault and that creep on all faults extends to depth perhaps as great as 100 km, the geodimeter results can be accounted for with no accumulation of strain. Scholz and Fitch (1970, p. 4447) also pointed out that measurements of creep on these minor faults must be made before seismic risk can be predicted.

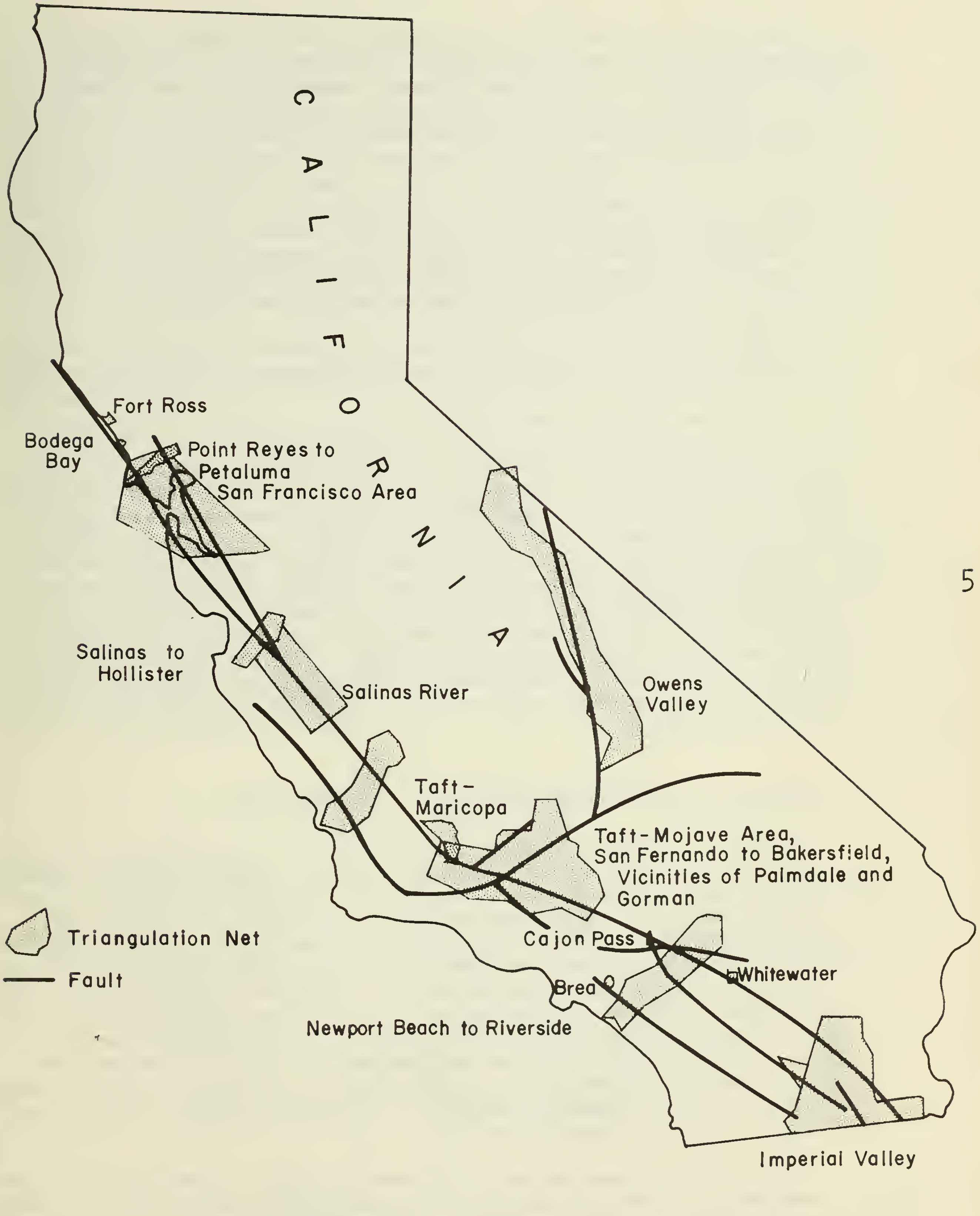


Figure 2 Triangulation nets for crustal movement studies

Savage and Burford (1970) have made a thorough analytical review of triangulation data from five tectonically active areas of California: Hollister, Cholame, Santa Barbara Channel, Owens Valley, and Imperial Valley. They found no evidence for strain accumulation in the Hollister area from 1930 and 1962, in the Santa Barbara Channel from 1880 to 1923, and in the Owens Valley from 1934 to 1954. Near Cholame, accumulation of shear strain along the San Andreas fault between 1932 and 1962 appears to have been directly caused by slip a few miles to the north, which accompanied the 1934 Parkfield earthquake; no significant strain accumulation occurred there from 1951 to 1962. In Imperial Valley, however, they found an average accumulation of 0.4 ppm/yr right-lateral shear strain parallel to the Imperial fault, extending over a zone perhaps 100 km wide.

In their discussion of Scholz and Fitch's work (1969, 1970), Savage and Burford (1971) reiterated their view that fault slip accounts for the geodetic observations of crustal movement on the central San Andreas fault between San Juan Bautista and Cholame. They cited both the recent fault-creep observations and the apparent rigid behavior of crustal blocks flanking this section of the fault. Similarly, they showed that data from geodimeter lines crossing the Hayward and Calaveras faults are compatible with right-lateral block movement at the higher creep rates recently observed on these faults. In the San Francisco Bay Area, the geodimeter and triangulation data do not prove that strain is accumulating there; according to Savage (1971, p. 815), "...sensible strain accumulation obtains only within a zone extending a few kilometers on either side of the major faults, and, consequently, strain accumulation is not easily distinguished from fault creep." Nason (1971, p. 191) concurred in these findings, saying that "...the geodimeter measurements do not indicate a large elastic strain accumulation of the type suggested by Scholz and Fitch (1969, 1970)."

The Feasibility of Earthquake Warning

To "predict" means to tell or declare beforehand; foretell; prophesy. To "warn" means to caution or notify of possible danger or risk. A warning, therefore, does not connote the certainty of a prediction. Fully scientific earthquake prediction may not be possible for many years because many physical parameters would probably have to be monitored accurately to provide sufficient information. These parameters include stress, strain, temperature, water content, and mechanical properties (viscoelastic constants) in and of the rocks at depths to 15 km or more in the earth's crust. All of these can now be measured on the surface or at depths to 1 or 2 km. Sub-surface measurements are extremely expensive, however, and are not presently feasible at depths greater than perhaps 5 km. An adequate program of near-surface measurements employing current technology would cost many millions of dollars annually.

A short-term warning capability, however, may be closer at hand. Field observations, laboratory experiments, and theory all indicate that anomalous earth deformation may occur and should be detectable prior to the occurrence of shallow-focus earthquakes. In California, data from seismograph networks have shown that earthquakes occurring in the San Andreas fault system have focal depths no greater than 15 km. This suggests that, above 15 km, the crust is relatively brittle (assuming earthquakes occur by a process of brittle fracture), whereas, below that depth, crustal rocks are relatively plastic. Presumably, an earthquake occurs when progressive plastic deformation (creep) in the lower crust loads the brittle upper crust to its breaking strength.

Laboratory experiments in rock mechanics have shown that, under certain conditions, creep in peridotite and dunite may be unstable and may accelerate in exponential fashion; that is, the creep rate is an exponential function of applied stress (Scholz, 1971, p. 127). In this fashion, linear accumulation of strain and stress at depth in the near-fault region could give rise to accelerating creep on deeper reaches of the fault itself. This accelerated creep should be observable at the surface as accelerated strain and tilt.

It is not to be expected that all such accelerated-strain events will be followed by significant earthquakes: Major (1971, p. 154-155) has observed frequent aseismic-strain episodes on strain meter records from the Aleutian Islands, which he associated with creep episodes on a deep shear zone. However, the proportion of aseismic- to seismic-strain episodes may be expected to vary with tectonic regime, and it may be that in certain regions all strain episodes with geographic extent and magnitude above some threshold values should be the basis for issuing earthquake warnings. Furthermore, experience may show that strain episodes that are short-term precursors of earthquakes have unique characteristics. Hence, earthquake warnings having a high probability of "success" may become possible on an empirical basis without thorough and detailed knowledge of all parameters affecting earthquake occurrence.

MEASUREMENT BY SURVEYING METHODS

Geodetic Triangulation

Instrumental measurement of crustal movement in California began in 1906, when the U.S. Coast and Geodetic Survey (USC&GS), now the National Ocean Survey, reobserved their triangulation network in the San Francisco Bay region. Between 1851 and 1887, the USC&GS established a primary (first-order) triangulation net in the San-Francisco-Bay-to-Monterey-Bay region. The 1906-07 resurvey revealed that right-lateral displacement decreased with distance from the San Andreas fault. These data were thoroughly analyzed by H. F. Reid (1910, p. 16-28) and provided the basis for his elastic rebound theory of earthquake generation. The primary net in the San Francisco Bay Area was reobserved in 1922, and the results of this and the 1906-07 resurvey formed the basis for a systematic program of special-pattern surveys to study horizontal movement along the San Andreas fault. These surveys have been described by Meade (Meade and Small, 1966; Meade, 1963, 1968, 1970), and their locations and data are briefly summarized here in table 2 and figure 3.

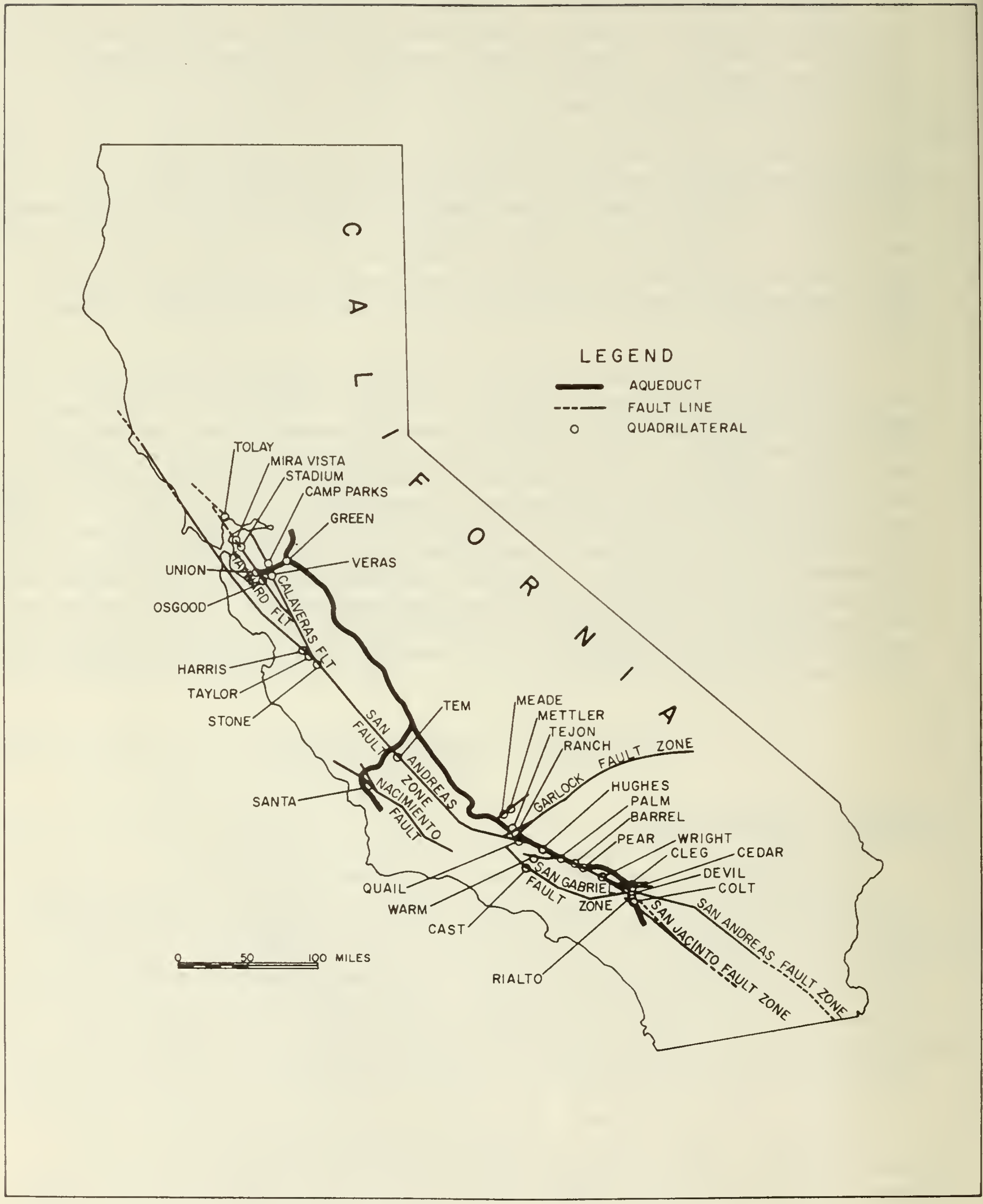


Figure 3 Quadrilaterals at aqueduct-fault crossing sites

Table 2. Locations and data on triangulation nets for crustal movement studies of the National Ocean Survey (formerly the U.S. Coast and Geodetic Survey).

Location (vicinity)	Dates of surveys	Results and references
Fort Ross	1876, 1909, 1969	No slip on San Andreas fault since 1906; right-lateral strain accumulation about 1 ppm/yr[1].
Bodega Bay	1968, 1969	No significant change (also trilaterated)[1].
Pt. Reyes to Petaluma	1930, 1938, 1948, 1960	Right-lateral movement about 1 cm/yr near San Andreas fault[2]; appears to be strain, not slip.
San Francisco Bay Area	1882, 1906, 1922, 1945, 1951, 1957, 1963, 1969	Right-lateral displacement 5 to 6 cm/yr between Mt. Diablo and San Francisco Peninsula[2]; both fault slip and strain take place.
Salinas to Hollister	1930, 1951, 1961	Right-lateral slip 1.6 cm/yr on San Andreas fault[2]; total shift across arc about 2.6 cm/yr[3].
Salinas River	1944, 1963	Right-lateral slip 3 cm/yr on San Andreas fault[2].
San Luis Obispo to Avenal	1932, 1951, 1962, 1966	Right-lateral slip 15 cm for 1932-51 on San Andreas fault; none for 1951-62; total right-lateral shift across arc 1.5 cm/yr for 1932-51[3].
Taft to Maricopa	1932, 1959	Compression 2 to 3 cm/yr across Buena Vista thrust fault[4].
San Fernando to Bakersfield	1932, 1952-53, 1963	No significant data[4,5].
Taft to Mojave	1959-60, 1967-68	Strain rates roughly 1 ppm/yr with right-lateral shear parallel to San Andreas fault west of Gorman; east of Gorman, strain axes have scattered orientations[6].
Imperial Valley	1935, 1941, 1954, 1967	Regional right-lateral displacement 8.5 cm/yr for 1941-67[7]; right-lateral shear strain about 50 ppm parallel to Imperial fault for 1941-67[8].
Owens Valley	1935, 1956	No significant movement detected[4].
Gorman	1938, 1949, 1966	No significant movement detected[9].
Palmdale	1938, 1947, 1958	No significant movement detected[4].
Cajon Pass	1949, 1963	No significant movement detected[2].
Brea	1938, 1949, 1966	No significant movement detected[10].
Newport Beach to Riverside	1929, 1933, 1953	No significant movement detected[4].
Whitewater	1950 (partly surveyed 1930)	No significant movement detected[10].

[1] Meade, 1970

[2] Meade and Small, 1966

[3] Burford, 1967

[4] Meade, 1963

[5] Miller *et al.*, 1969b

[6] Miller *et al.*, 1969a

[7] Scholz and Fitch, 1969

[8] Miller *et al.*, 1970

[9] Meade, 1968

[10] Meade, 1971, personal communication

Local Triangulation

Creep on the San Andreas fault was discovered in 1956 when Steinbrugge and Zacher (1960) investigated damage at the Taylor (also called Almaden or Cienega) Winery, which sits directly astride the fault about 7 miles (11 km) south of Hollister. Reinforced concrete walls and concrete slab floors were cracked, and progressive deformation had thrown some columns so far out of plumb that they had to be rebuilt in 1954. Subsequently, the USC&GS set up a small quadrilateral figure across the fault on the north side of the winery, which has been resurveyed annually since 1957. Results show that creep movement averages 1.5 cm/yr (Meade, 1966, p. 387). The first creep recorder was installed in the winery in 1957 (Tocher, 1960) and has indicated an average rate of 1.3 cm/yr.

In 1960, creep was discovered on the Hayward fault by Cluff and Steinbrugge (U.S.G.S., 1966, p. 8-12), who found a building apparently damaged by right-lateral movement on the fault. Since then, right-lateral offset of culverts, sidewalks, railroad tracks, and other structures has been found at several places along the Hayward fault between Berkeley and Fremont (U.S.G.S., 1966).

Thus, it was recognized in the early 1960s that creep could be a major hazard to engineering structures, and consequently the California Department of Water Resources supported the USC&GS in a cooperative effort to monitor creep at locations where the California Aqueduct would cross active faults. In 1964 and 1965, quadrilateral figures several hundred meters across were set up at 21 aqueduct-fault intersections (figure 4). Most have been resurveyed annually or biannually since then. These sites are on the San Andreas, Hayward, and Calaveras faults; the Sunol and Pleasanton branches of the Calaveras fault; and the Nacimiento, White Wolf, San Jacinto, and Cleghorn faults. Creep has been measured at sites on the first five in the greater San Francisco Bay region; elsewhere measured changes in figures are questionable and largely within the range of probable error.

Since 1966, the Seismological Laboratory of the California Institute of Technology has established about 38 fault-crossing angulation nets having maximum dimensions of about 400 m. In these nets, lateral fault displacement is determined by monitoring angular changes between lines radiating from a point on one side of the fault to several points on the other. These nets are chiefly in southern California south of the Transverse Ranges on the San Andreas, San Jacinto, Superstition Hills, Elsinore, Coyote Creek (branch of the San Jacinto), and Imperial faults; there are also several on the central San Andreas fault (Clarence R. Allen, 1971, personal communication); see figure 1 for fault locations. Nets on the central San Andreas fault have been observed up to 40 times; on the Imperial and Coyote Creek faults, 12 times; and others from one to nine times. In the Imperial Valley region, "definite or suspected movements have been observed along parts of the San Jacinto, Coyote Creek, Superstition Hills, Imperial, and San Andreas faults; no movement has been detected along the Elsinore and Superstition Mountain faults or along the San Andreas-Banning-Mission Creek fault system northwest of Mecca Hills" (Hileman _et al_., 1971).

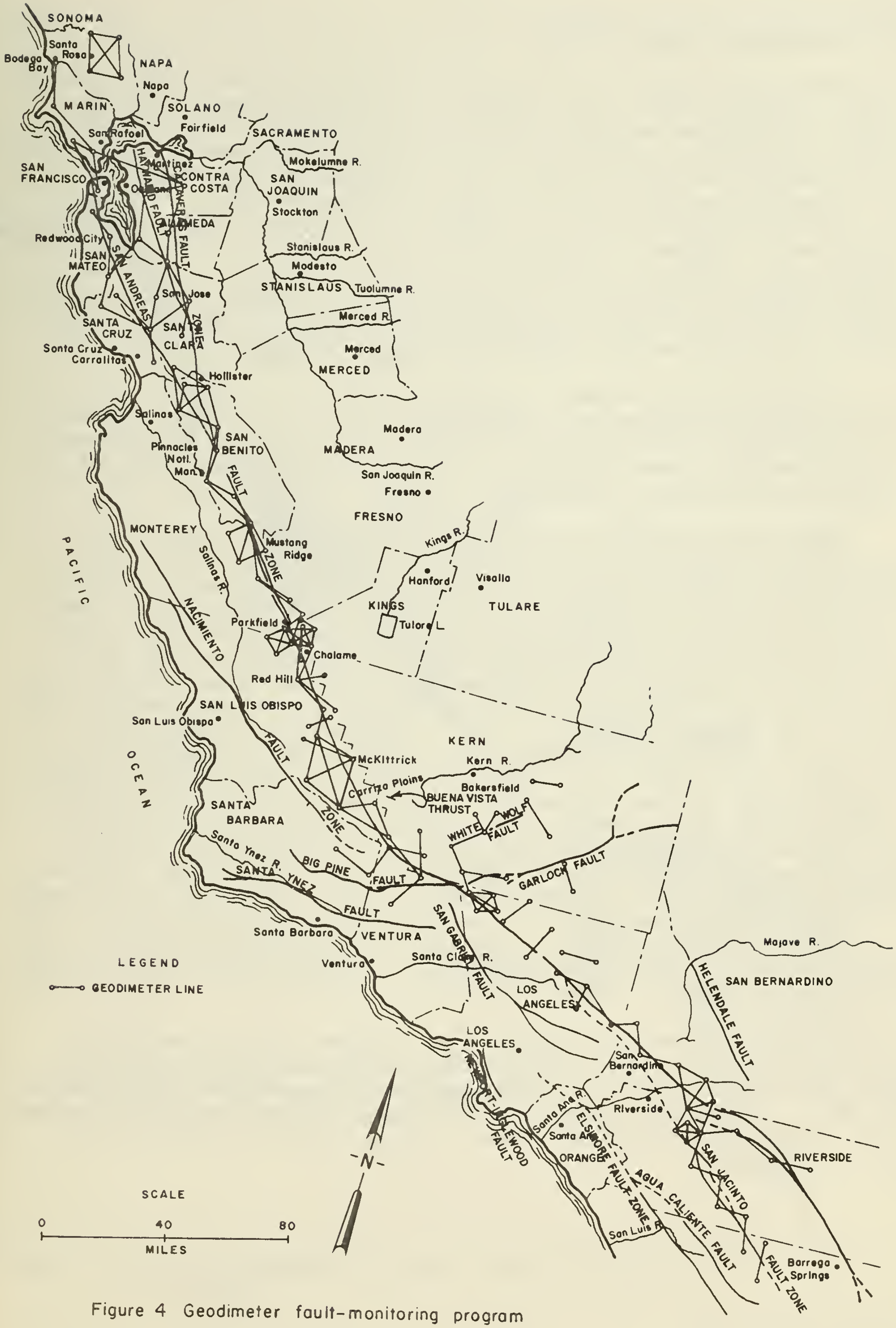


Figure 4 Geodimeter fault-monitoring program

Electro-Optical Distance Ranging

When construction of facilities of the California State Water Project began in the late 1950s, the Department of Water Resources' Consulting Board for Earthquake Analysis recommended a program to measure rates of crustal movement in the neighborhood of active faults. Chains of geodimeter (see Glossary) survey lines were established crisscrossing faults of the San Andreas system from San Francisco to Palm Springs (figure 5). The work consisted almost entirely of repeated measurements of the lengths of these lines. Progress of the project to early 1968 has been described by Hoffman *et al*. (1968). In 1968, the California Division of Mines and Geology assumed responsibility for the geodimeter program and considerably augmented the original survey scheme, adding a number of closed figures as well as "crisscrossing" lines (Greensfelder and Crice, 1971, p. 109).

Distances can be determined by geodimeter to an accuracy of about 10 times that of first-order triangulation, which is normally accurate to about 10 ppm (see Glossary). This means that gradual crustal movement can be detected in one-tenth the time period (reobservation interval) required by triangulation methods.

Measurements on more than 100 lines have been made annually or as frequently as possible since 1959. Most of these lines cross faults at angles smaller than 30 degrees and are therefore particularly useful for detecting strike-slip movement. In the following discussion, the term "movement" is used in describing the geodimeter data because these data actually express the combined displacements attributable to both fault slip (creep or earthquake-slip) and strain in the near-fault region. Other data must be examined to distinguish the part of total displacement due to creep from the part due to strain. Comparison of geodimeter measurements with those obtained from creepmeters and alignment arrays (discussed later) shows that long-term (10 years or more) change in line lengths is much greater where fault creep occurs than where it does not. In other words, in the zone occupied by the geodimeter lines--generally about 10 km wide and centered on a fault trace--displacement of points on one side of the fault trace relative to points on the other, hence the change in length of lines connecting those points, is much greater where fault creep occurs than where it does not, over a period of 10 years. This is due simply to the fact that creep-displacement is concentrated on the fault itself while strain-displacement may be spread across a zone perhaps tens of kilometers wide (see figure 6).

The greatest average movement rates detected over the past decade occurred on the San Andreas fault between the Pinnacles and Parkfield, where movement has been relatively steady at rates of about 3 to 3½ cm/yr (figure 7). Beyond this segment of the fault, movement diminishes markedly, corresponding with the disappearance of creep north of Watsonville and south of Cholame.

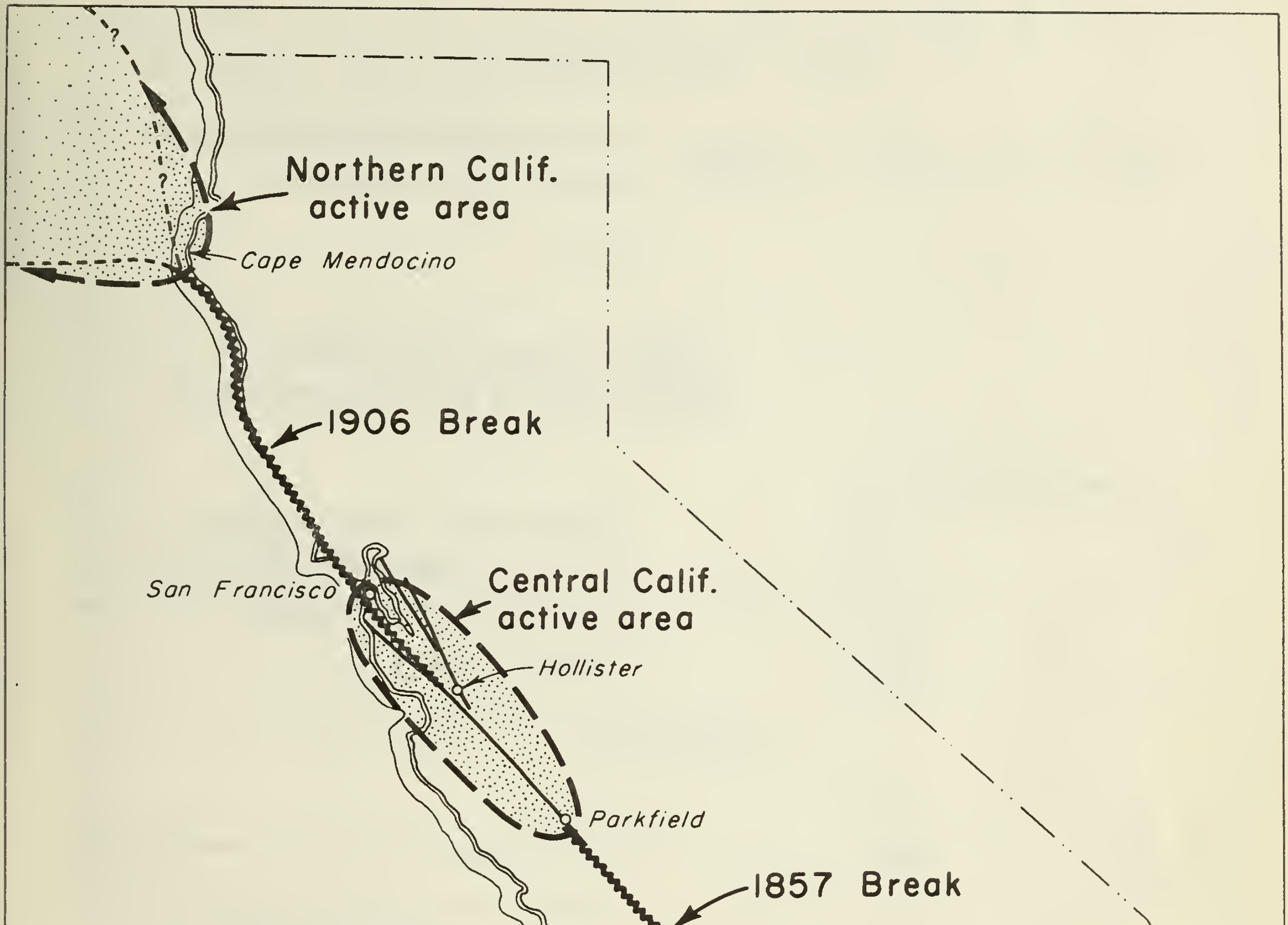
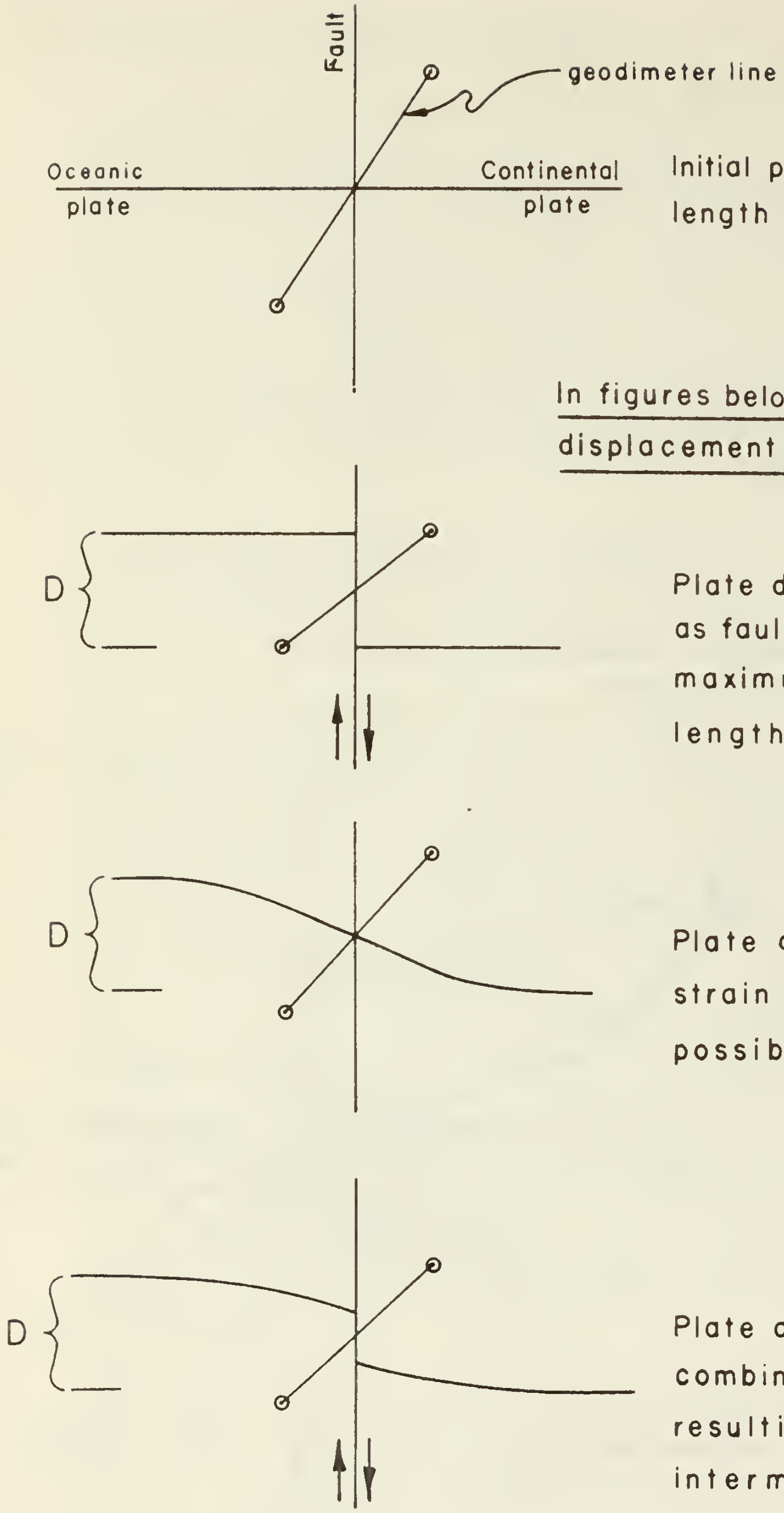


Figure 5 Areas of contrasting seismic behavior along the San Andreas fault zone in California.

(From Allen, 1968, page 72)



Initial position tectonic plates and length of geodimeter line.

In figures below, tectonic plate displacement is equal to constant, D.

Plate displacement D appears as fault creep only, resulting in maximum possible geodimeter line length change.

Plate displacement D appears as strain only, resulting in minimum possible line length change.

Plate displacement D appears as a combination of creep and strain, resulting in line length change intermediate to above extreme cases.

Figure 6 Diagram showing the effects of fault creep and strain on geodimeter line length (exaggeration = 10^5).

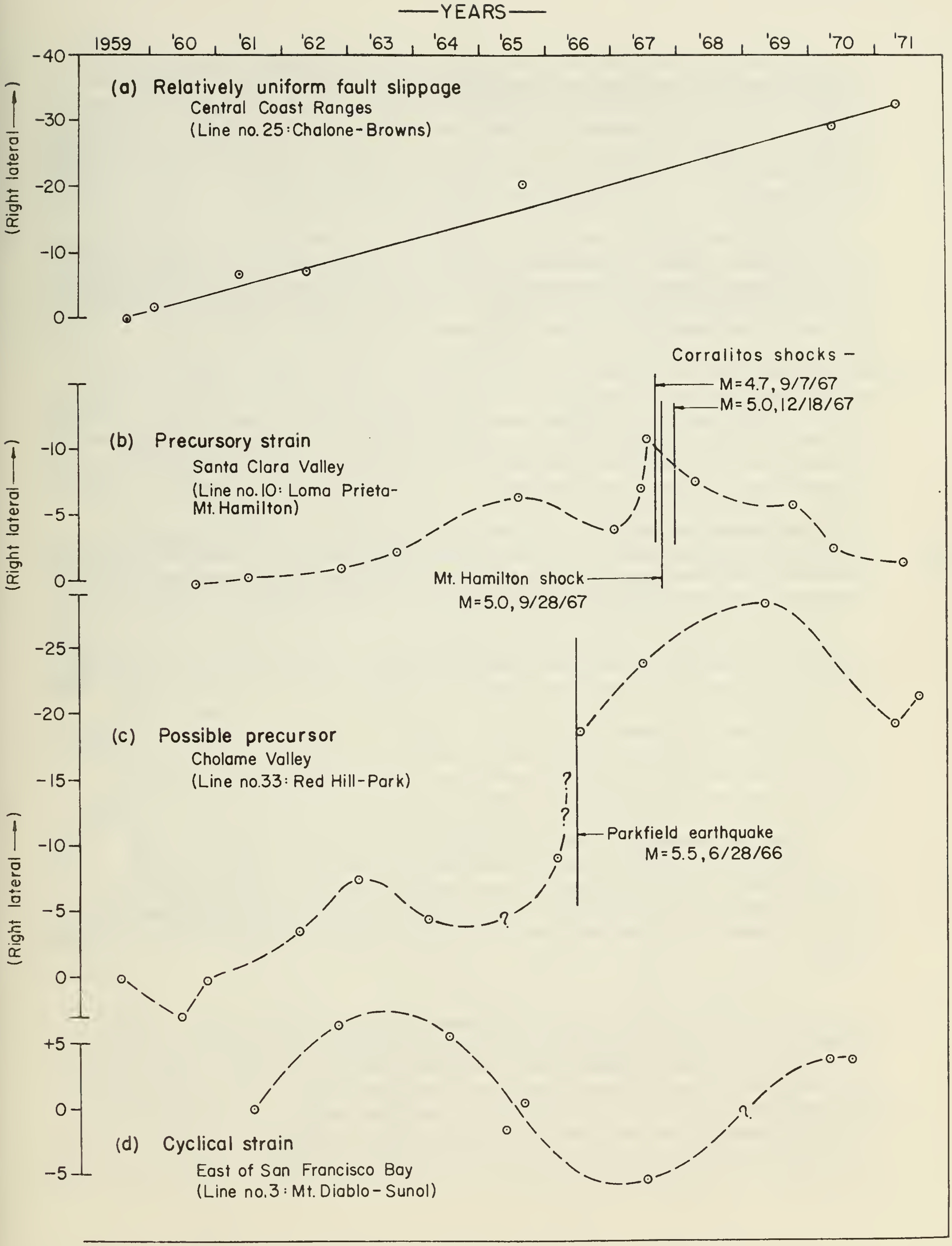


Figure 7 (a,b,c,d) Geodimeter Line Length: varying types of behavior

Geodimeter lines across the Hayward fault indicate right-lateral movement averaging 1½ cm/yr; comparable motion appears across the Calaveras fault south of its "junction" with the Hayward fault. North of the "junction", however, movement across the Calaveras dies off to near zero between Mt. Hamilton and Mt. Diablo. Thus it appears that some creep on the San Andreas fault south of Hollister is transferred to the Calaveras fault, and this in turn is shifted to the Hayward fault.

In the Santa Clara Valley and Hollister region and in Cholame Valley, the geodimeter line lengths have behaved in an erratic fashion which can be correlated with the occurrence of local earthquakes (Hoffman et al., 1968; Greensfelder and Crice, 1971). A strain event appears to have preceded the Corralitos or Mt. Hamilton earthquakes of fall 1967. On September 7 and December 18, earthquakes of magnitude 4.7 and 5.0 respectively occurred near Corralitos and within 10 km of Loma Prieta; on September 28, an earthquake of magnitude 5.0 occurred a few kilometers south of Mt. Hamilton. Fortuitously, the geodimeter line between Mt. Hamilton and Loma Prieta was observed on three occasions between January and July 1967, an unusually close spacing of measurements. These observations indicate an anomalously high rate of strain during the six months immediately preceding the three earthquakes (figure 7b). In addition, measurements on two other lines radiating from Mt. Hamilton to Allison and Morgan show consistent right-lateral strain steps during the interval from mid-July to early October. This suggests that the apparent precursor was most directly associated with the Mt. Hamilton shock.

In the Cholame Valley area, length changes observed on the line from Red Hills to Park prior to the 1966 Parkfield earthquake are limited but perhaps similar to those described above (figure 7c). Unfortunately, only one measurement was obtained on this line during the two years before the earthquake; however, the strain reversal in 1963-64, similar to that seen on the line from Loma Prieta to Hamilton, suggests that frequent observations on the line from Red Hills to Park might have revealed strain acceleration similar to that observed on Loma Prieta to Hamilton.

Along the segment of the San Andreas fault from Cholame to San Bernardino, the data indicate no fault slip and only slight strain accumulation. Strain accumulation is indicated in the San Bernardino region across the San Andreas and San Jacinto fault zones and takes the form of north-south compression at a rate of about ½ ppm/yr (Hoffman et al., 1968, p. 69).

In a recent review of the geodimeter data, workers of the California Division of Mines and Geology have found strong evidence for a cyclical variation of dilational strain with amplitude of 2 to 3 ppm and a period of about seven years (figure 7d). This effect appears to be synchronous from San Francisco to San Bernardino. Because of the low frequency of observation, the effect is clearly discernible only on lines which are not disturbed by the much larger effect of fault slip.

Other organizations have begun to apply electro-optical ranging to the measurement of crustal movement. The National Center for Earthquake Research (NCER) of the U.S. Geological Survey (USGS) began its monitoring program in 1965 and by 1970 had established eight small nets in the region from San Francisco Bay to Hollister. Seven cross the San Andreas fault, and one crosses the Calveras fault. Four have been monitored fortnightly; and the others, annually. In 1970, NCER triangulated and trilaterated (trilateration in this case is performed by electro-optical ranging) most of the network from Salinas to Hollister, which the USC&GS triangulated in 1930, 1951, and 1962. The 1970 data are consistent with those of the earlier surveys, indicating continued right-lateral block motion of 2½ cm/yr across the oombined San Andreas, Sargent, and Calaveras faults. In 1971, the Salinas-to-Hollister network was extended to Gilroy.

The National Ocean Survey (NOS), formerly the USC&GS, began trilateration in 1969 in the Anza-Borrego Desert area, as a result of the 1968 Borrego Mountain earthquake. In 1969, NOS also trilaterated the Fort Ross net and established a new trilateration net in the Bodega Bay area. In 1970, they established a new trilateration net in the Stone Canyon area about 16 miles southeast of Hollister.

The Geology Department of the University of California at Santa Barbara established a trilateration net in 1970 across the Santa Barbara Channel, an area of high seismicity. This net probably will be reobserved in about five years. In 1970, the Department of Geological Sciences at the University of California at Riverside--in cooperation with Imperial College, London, U.K.--set up a long trilateration arc across the Imperial fault; the arc was reobserved twice in 1971, but results have not yet been published.

Leveling

The U.S. Coast and Geodetic Survey began leveling work in California in 1906 and, since then, has completed about 30,000 miles of first-order and 20,000 miles of second-order leveling and releveling (Meade and Small, 1966, p. 390). The most intensive releveling has been in the San Joaquin Valley where rapid subsidence, due largely to ground water withdrawal, poses a continuing hazard to the operation of hydraulic systems, particularly the California Aqueduct. More than 22 feet of subsidence has occurred 16 km southwest of Mendota (Meade and Small, 1966, p. 390).

In 1935, five level lines were established across the San Andreas fault between Maricopa and Whitewater in the San Jacinto Mountains; these were releveled from two to eight times by 1966 (Meade and Small, 1966, p. 391). These and other level data have been insufficiently analyzed, for the most part, to allow the drawing of significant conclusions concerning vertical tectonic movements. However, on the basis of releveling between Mettler, in the southern San Joaquin Valley, and Gorman, in the Tehachapi Mountains, Lofgren (1966) concluded that uplift accompanying the 1952 Kern

County earthquakes reached a maximum of about 0.6 m (nearly 2 feet) in the Wheeler Ridge area and that vertical tectonic movement has continued in the Tehachapi Mountains since 1952. This continuing movement has an axis of flexure about 2 miles south of Grapevine, but absolute vertical movement is unknown.

The NCER, in 1968, set up several short level lines across the San Andreas fault on the San Francisco Peninsula and, in 1969, established several "tilt arrays"--actually very small leveling arrays--on the Calaveras, San Andreas, and Coyote Creek faults. The Geology Department of the University of California at Santa Barbara, in 1970, set up seven fault-crossing level lines in the vicinity of Santa Barbara and four such lines in Death Valley. Significant vertical movement has not been reported on any of these lines or arrays.

CONTINUOUS-MONITORING INSTRUMENTS

Creepmeters and Alignment Arrays

Since 1964, the Earthquake Mechanism Laboratory of the National Oceanographic and Atmospheric Administration and the National Center for Earthquake Research of the U.S. Geological Survey have put about 60 creepmeters and 58 alignment arrays into operation. Creepmeters and alignments are frequently located at the same sites to enable determination of the fraction of fault slip recorded by the creepmeters.

Data from alignment arrays indicate that most fault displacement occurs in a zone less than 6 m wide at most sites (Raleigh and Burford, 1969, p. 380). Creepmeters have shown that fault creep is episodic at most sites, the episodes being called creep events, and that the episodes are not simultaneous at different sites but propagate along the fault at apparent rates of less than 10 km/day. Most creep events involve fault segments up to 20 km long (Nason, 1971, p. 31).

Creepmeters, alignment arrays, and offset structures show that the maximum slip-rate on the San Andreas fault is about 2.5 cm/yr and occurs on the segment between Bear Valley, north of San Benito, and Middle Mountain, north of Parkfield, a distance of about 90 km (see figure 1 for locations). Northward from Bear Valley, fault slip dies out to zero near Watsonville; southward from Middle Mountain, slip drops to zero a short distance south of Cholame (Nason, 1971, p. 7-13). Slippage on the most active central segment is almost entirely aseismic; however, a significant fraction of slippage on the end-segments may have occurred during moderate-magnitude (M=4 to 6) earthquakes.

Active slippage has been observed along the Hayward fault from San Pablo to Fremont at rates of 0.5 to 0.7 cm/yr. On the Calaveras fault, movement decreases from a maximum of 1.5 cm/yr at Anderson Reservoir, 20 km south of Mt. Hamilton, to 0.6 cm/yr in Hollister. North of Mt. Hamilton, little, if any, slip is occurring (Nason, 1971, p. 14-16).

Strain Meters

The quartz-rod strain meter was designed by Hugo Benioff (1959, p. 1019-1032) for secular, tidal, and seismic-strain measurements. This instrument was first installed at Dalton about 33 km northwest of Pasadena in 1953. Since then, similar instruments have been installed at Mt. Palomar (1954), Lake Isabella (1957), and Pasadena (1959). The quartz-rod strain meter has an intrinsic strain sensitivity approaching 10^{-10}; however, useful sensitivity in the ultra-long-period range (from one day to one year and longer) is limited by background noise caused chiefly by temperature variations at the ground surface and at the instrument, as well as by fluctuations in barometric pressure and ground water levels.

A quartz-rod strain meter was installed in 1967 at the Earthquake Mechanism Laboratory's Stone Canyon Observatory 30 km south of Hollister (Bufe *et al.*, 1970). The Seismographic Station of the University of California at Berkeley established its San Andreas Geophysical Observatory (SAGO) north of the Taylor (Almaden) Winery in 1968; a quartz-rod strain meter is included in its complement of instruments.

The Institute of Geophysics and Planetary Physics (IGPP) of the University of California at San Diego has designed, built, and recently installed two laser-interferometer strain meters which have a sensitivity of 10^{-10} and operate over an 800 m base above ground level. One is located at Camp Elliot near San Diego; and the other, at Pinyon Flat in the Santa Rosa Mountains. The Pinyon Flat instrument has been operating for more than a year, and its record shows an apparent annual strain cycle with amplitude about ½ ppm.

These instruments have not yet provided significant information on secular strain changes although their data have been quite useful in the study of very long-period seismic surface waves.

Tiltmeters

Ten "permanent" tiltmeter stations are currently in operation. The first, a two-component mercury type, was installed at Lake Isabella in 1964 by the California Institute of Technology. EML installed a two-component mercury tiltmeter at Stone Canyon in 1966 and, more recently, a similar instrument near the Buena Vista fault. Between 1969 and 1971, NCER installed two-component mercury tiltmeters at San Francisco, Berkeley, Mt. Hamilton, and Fremont Peak southwest of Hollister. The California Division of Mines and Geology has recently installed three biaxial electrolytic-bubble type tiltmeters along the San Andreas fault, one in Cholame Valley and two in the Carrizo Plain area.

Anomalous tilt events have been observed prior to earthquakes in Japan, where tiltmeters have been operated for many years. During the 1966 Matsushiro earthquake swarm, rapid accelerations in ground tilting were observed beginning several hours before earthquakes of magnitude 4½ or greater (Hagiwara and Rikitake, 1967, p. 765).

The Danville (M=4.0) earthquakes of June 11 and 12, 1970, on the Calaveras fault zone about 25 km east of Oakland were preceded by a very interesting tilt event which began 29 hours before the first shock. The event was recorded on the Berkeley and San Francisco Presidio instruments operated by NCER (Wood _et_ _al_., 1971). Twenty-nine hours before the first shock, the Berkeley tilt-vector, which had been pointing down and parallel to the Hayward fault, began to swing around toward the earthquake epicenter. Thirteen hours before the first shock, the vector had stabilized in the direction of the epicenter, where it remained until after the second shock when it swung back parallel to the fault but 180 degrees from its initial azimuth. These data suggest that tiltmeters may be key elements in an earthquake warning system.

GLOSSARY

Alignment array. An initially straight row of monuments set at right angles across an active fault trace; progressive fault slip is observed by repeated observation of horizontal displacement of these monuments from their initial positions relative to each other.

Arc. A long, narrow triangulation or trilateration network, generally a chain of quadrilateral survey figures.

Creepmeter. A displacement meter for measuring creep. It actually measures the change in distance between two monuments (generally about 10 m apart) on opposite sites of a fault trace. Typically, the instrument provides a continuous chart recording of displacements.

Dilatation. A parameter of strain, which is equal to the change in area per unit area. It may be thought of as an omni-directional extension or contraction.

Geodimeter. The trade name for one of the most common electro-optical distance measuring instruments. "Geodimeter" is often used generically to denote all such instruments. The instrument is capable of measuring distance with an error less than 1 ppm; this amounts to 1 mm in 1 km.

Part(s) per million (ppm). One part per million is equal to 1/1,000,000.

Strain. In its most general sense, strain is the deformation of a body due to stress or force. As used in this paper, strain has the restricted meaning of continuous deformation in a horizontal plane; that is, plane strain. Strain is expressed as a change in length per unit length in a given direction; this quantity is a dimensionless number and is here stated in parts per million (ppm).

Strain meter. An instrument for measuring deformation due to stress or force. In geophysical applications, the quartz-rod extensometer is most commonly used. This instrument typically operates over a base 10 to 30 m long and has a sensitivity of .001 ppm or better; it actually measures change in distance between two monuments, the quartz rod serving as a constant-length reference.

Tiltmeter. An instrument for measuring change in the attitude or slope of the local ground surface.

Triangulation. The process of measuring the angles necessary to determine the precise positions of monuments in a trigonometric survey; in this process, the Earth's surface is divided into a series of triangles. A transit or theodolite is the instrument used to measure these angles.

Trilateration. The process of measuring the lengths necessary to determine the precise positions of monuments in a trigonometric survey. An electronic or electro-optical distance ranging instrument, such as a geodimeter, is normally used in such a survey.

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MAP INDEX

LARGE TRIANGULATION NETWORKS AND ARCS

Map no.	Region	Survey dates	Agency	References
NA 1	Eel River Basin	1966 (partly trilaterated 1966, 1969)	*NOS/DWR	Hoffman et al., 1968
NA 2	Fort Ross	1876, 1906, 1969 (trilaterated in 1969)	NOS	Meade, 1970
NA 3	Bodega Bay	1969	NOS	Meade, 1970
NA 4	Pt. Reyes to Petaluma	1930, 1938, 1948 partly, 1960	NOS	Meade and Small, 1966
NA 5	San Francisco Bay Area	1882, 1906, 1922, 1945, 1951, 1957, 1963, 1969 partly	NOS	Meade and Small, 1966
NA 6	Camp Parks	1969 (partly trilatered)	NOS	U.S. Coast and Geodetic Survey, 1970
NA 7	Salinas to Hollister	1930, 1951, 1962	NOS	Meade and Small, 1966; Burford, 1967
NA 8	Salinas River Valley	1944, 1963	NOS	Meade and Small, 1966
NA 9	San Luis Obispo to Avenal	1932, 1951, 1962	NOS	Burford, 1967
NA 10	Taft to Maricopa-Buena Vista	1932, 1938, 1949, 1959	NOS	Meade, 1963
NA 11	Taft-Mojave	1959-60, 1967-68	NOS/DWR	Miller et al., 1969a
NA 12	San Fernando-Bakersfield	1932, 1952, 1953, 1963 (north part)	NOS	Miller et al., 1969b
NA 13	Sandburg--Wheeler Ridge	1964	NOS/DWR	U.S. Coast and Geodetic Survey, 1970 and 1971
NA 14	Gorman	1938, 1949, 1966	NOS	Meade, 1968
NA 15	Fairmont-Castaic	1964	NOS/DWR	
NA 16	Palmdale	1938, 1947, 1958	NOS	Meade, 1963
NA 17	Valyermo-Palmdale	1964	NOS/DWR	
NA 18	Cajon Pass	1949, 1963-64	NOS	Meade and Small, 1966
NA 19	Perris-Cedar Springs	1964	NOS/DWR	
NA 20	Newport Beach to Riverside	1929, 1934, 1963	NOS	Meade, 1963
NA 21	Brea	1938, 1949, 1966	NOS	Meade, 1971, personal communication
NA 22	Moreno	1950	NOS	Meade, 1971, personal communication
NA 23	Whitewater	1950	NOS	Meade, 1971, personal communication
NA 24	Imperial Valley	1935, 1941, 1954, 1967	NOS	Miller et al., 1970
NA 25	Owens Valley (not shown)	1935, 1956	NOS	Meade, 1963

*Key to abbreviations on last page of index.

SMALL TRIANGULATION NETS (FAULT-CROSSING)

Map no.	Locality and site name	Fault	Observation dates	Agency	References
Q 1	Black Point: Tolay	Hayward	1965, 1967 (discontinued)	NOS/DWR	*
Q 2	Olema: Olema	San Andreas	1906, 1944, 1957, 1963	NOS	+
Q 3	El Cerrito: Mar	Hayward	1966, 1968, 1970	NOS	+
Q 4	U.C. Berkeley: Stadium	Hayward	1966, 1967, 1969	NOS	+
Q 5	Pleasanton: Camp Parks	Calaveras-Sunol	1964, 1965, 1969	NOS/DWR	*
Q 6	Union City: Union	Hayward	1965, 1966, 1967, 1969	NOS/DWR	*
Q 7	Sunol: Veras	Calaveras	1965, 1966, 1970	NOS/DWR	*
Q 8	San Mateo: Crystal Springs Lake	San Andreas	1906, 1947, 1957, 1963	NOS	+
Q 9	Irvington: Craig (Osgood)	Hayward	1966, 1968, 1969	NOS	+
Q 10	Hollister: Hollister	Calaveras	1930, 1951, 1962	NOS	+
Q 11	Cienega Valley: Harris Ranch	San Andreas	1967, 1969	NOS	+
Q 12	Cienega Valley: Winery	San Andreas	1957, annually since 1959	NOS	+
Q 13	Cienega Valley: Stone Canyon	San Andreas	1967, 1968, 1969, 1970	NOS	+
Q 14	Death Valley: Stovepipe Wells	Furnace Creek		UCSB	A. Sylvester, personal communication, 1970
Q 15	Cholame: Tem	San Andreas	1964, 1965, 1966, 1968, 1970	NOS/DWR	*
Q 16	Santa Margarita: Santa	Branch of Nacimiento	1964, 1965, 1968	NOS/DWR	*
Q 17	Mettler: Mettler	White Wolf	1964, 1965, 1966, 1969	NOS/DWR	*
Q 18	Wheeler Ridge: Meade	White Wolf	1969	NOS/DWR	*
Q 19	Maricopa: Camp Dix	San Andreas	1969, 1970	TJC	L. Peahle, personal communication, 1970
Q 20	Tehachapi Mtns: Tejon	Garlock	1964, 1965, 1966, 1970	NOS/DWR	*
Q 21	Tehachapi Mtns: Ranch	Garlock	1964, 1965, 1966, 1967, 1968, 1969, 1970	NOS/DWR	*
Q 22	Gorman: Quail	San Andreas	1964, 1965, 1968, 1970	NOS/DWR	*
Q 23	Lake Hughes: Hughes	San Andreas	1964, 1965	NOS/DWR	*
Q 24	Palmdale: Palm	San Andreas	1964, 1965, 1966	NOS/DWR	*
Q 25	Castaic: Warm	Clearwater	1964, 1965	NOS/DWR	*
Q 26	Palmdale: Barrel	San Andreas	1964, 1965, 1966, 1967, 1970	NOS/DWR	*
Q 27	Santa Ynez Mtns: Alisal Ranch	Santa Ynez (north branch)	1971	UCSB	A. Sylvester, personal communication, 1971

SMALL TRIANGULATION NETS (FAULT-CROSSING)

Map no.	Locality and site name	Fault	Observation dates	Agency	References
Q 28	Pearblossom: Pear	San Andreas	1964, 1965, 1966, 1967, 1969	NOS/DWR	*
Q 29	Castaic: Cast	Near the San Gabriel	1964, 1965, 1967, 1970	NOS/DWR	*
Q 30	Jameson Lake: Juncal	Santa Ynez	1970, 1971	UCSB	A. Sylvester, personal communication, 1971
Q 31	Wheeler Springs: Wheeler Gorge	Santa Ynez	1971	UCSB	A. Sylvester, personal communication, 1971
Q 32	Santa Barbara: Mescalitan	More Ranch	1970	UCSB	A. Sylvester, personal communication, 1971
Q 33	Wrightwood: Wright	San Andreas	1964, 1965	NOS/DWR	*
Q 34	Cedar Springs: Cedar	Cleghorn	1964, 1965, 1967 destroyed	NOS/DWR	*
Q 35	San Bernardino: Devil	San Andreas	1964, 1965, 1966, 1968	NOS/DWR	*
Q 36	San Bernardino: Rialto	San Jacinto	1964, 1965, 1967, 1968, 1970	NOS/DWR	*
Q 36	San Bernardino: Colt	San Jacinto	1964, 1965, 1967, 1969, 1970	NOS/DWR	*

*Data of these surveys are periodically summarized in a series of informal (typewritten) reports, beginning 1965, with the general title "Results of triangulation for earth movement study at California Aqueduct fault-crossing sites", which are available from the National Ocean Survey.

+Surveys at these sites are described in informal reports of differing titles generally referring to triangulation for determination of earth movement. Available on a site-by-site basis from the National Ocean Survey.

TRILATERATION NETWORKS

Map no.	Locality	Survey dates and observation frequency	Agency	References
NL 1	Eel River Basin	1967	DWR	Hoffman _et_ _al_., 1968
NL 2	Bodega Bay	1967, 1969	NOS/DWR	Hoffman _et_ _al_., 1968; Meade, 1970
NL 3	Napa	1970	City of Napa	
NL 4	San Andreas Lake	1965--semiannually	NCER	Raleigh and Burford, 1969
NL 5	Calaveras	1969--annually	NCER	J.C. Savage, personal communication, 1970
NL 6	Portola Valley	1970--semiannually	NCER	J.C. Savage, personal communication, 1970
NL 7	La Honda	1969--annually	NCER	J.C. Savage, personal communication, 1970
NL 7	Black Mountain	1970--semiannually	NCER	J.C. Savage, personal communication, 1970
NL 8	Loma Prieta	1970--semiannually	NCER	J.C. Savage, personal communication, 1970
NL 9	Chase Ranch	1969--annually	NCER	J.C. Savage, personal communication, 1970
NL 10	Hollister	1969--annually	NCER	J.C. Savage, personal communication, 1970
NL 11	Reeves Ranch	1969--annually	NCER	J.C. Savage, personal communication, 1970
NL 12	Stone Canyon	1970--5-year intervals	NOS	Meade, 1970
NL 13	Peachtree Valley	1971--annually	DMG	DMG files
NL 14	Cholame Valley	1965, 1966, 1967 (part) 1969--annually	DWR/DMG	Hoffman _et_ _al_., 1968
NL 15	China Lake	1962, 1965	DWR	Hoffman _et_ _al_., 1968
NL 16	Gorman	1965, 1966, 1971	DWR/DMG	Hoffman _et_ _al_., 1968; Greensfelder, 1971
NL 17	Santa Barbara Channel	1971--5-year intervals	UCSB	A. Sylvester, personal communication, 1971
NL 18	Imperial Valley	1970, 1971	UCR/IC	T. Meidav, personal communication, 1970

SELECTED LEVEL LINES

Map no.	Locality and site	Date installed	Fault	Agency	References
L 1	Burlingame: Alcazar	1968	San Andreas	NCER	J. C. Savage, personal communication, 1970
L 1	San Andreas Lake: San Andreas Lake	1968	San Andreas	NCER	J. C. Savage, personal communication, 1970
L 2	Saratoga: Saratoga	1968	San Andreas	NCER	J. C. Savage, personal communication, 1970
L 3	Death Valley: Stovepipe Wells	1970	Death Valley-Furnace Creek	UCSB	A. Sylvester, personal communication, 1971
L 4	Death Valley: National Park Service Headquarters	1970	Death Valley-Furnace Creek	UCSB	A. Sylvester, personal communication, 1971
L 5	Death Valley: Mushroom Rock	1970	Artist's Drive	UCSB	A. Sylvester, personal communication, 1971
L 6	Death Valley: Hanaupah Canyon	1970	Hanaupah	UCSB	A. Sylvester, personal communication, 1971
L 7	Santa Ynez: Baseline	1970	Baseline	UCSB	A. Sylvester, personal communication, 1971
L 8	Santa Barbara: Jameson Lake	1970	Santa Ynez	UCSB	A. Sylvester, personal communication, 1971
L 9	Goleta: Golf Course	1970	Mesa	UCSB	A. Sylvester, personal communication, 1971
L 10	Santa Barbara: Crosstown	1970	Mesa	UCSB	A. Sylvester, personal communication, 1971
L 10	Santa Barbara: Lorinda and Portesuello	1970	Mesa	UCSB	Two lines 0.2 mile apart. A. Sylvester, personal communication, 1971
L 10	Santa Barbara: Cook	1970	Mesa	UCSB	A. Sylvester, personal communication, 1971
L 11	Santa Barbara: Burton Mound	1970	Mesa	UCSB	A. Sylvester, personal communication, 1971

SMALL ANGULATION ARRAYS (FAULT-CROSSING)
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Map no.	Locality	Fault	First observation	Number of observations to 1-1-71	References
A 1	Mustang grade	San Andreas	5-5-67	10	C. R. Allen, personal communication, 1970
A 2	Slack Canyon	San Andreas	6-7-67	8	C. R. Allen, personal communication, 1970
A 3	Classen Ranch	San Andreas	8-15-66	20	C. R. Allen, personal communication, 1970
A 4	Parkfield	San Andreas	7-7-66	26	Allen and Smith, 1966
A 4	Taylor Ranch	San Andreas	6-29-66	20	Allen and Smith, 1966
A 4	Peacock	San Andreas	7-7-66	35	Allen and Smith, 1966
A 4	Cemetery	San Andreas	7-8-66	9	Allen and Smith, 1966
A 4	Carr Ranch	San Andreas	6-30-66	40	Allen and Smith, 1966
A 5	Cholame	San Andreas	7-1-66	32	Allen and Smith, 1966
A 6	Christmas Canyon	Garlock	2-1-71		C. R. Allen, personal communication, 1970
A 7	Randsburg	Garlock	2-1-71		C. R. Allen, personal communication, 1970
A 8	Cameron	Garlock	2-1-71		C. R. Allen, personal communication, 1970
A 9	Una Lake	San Andreas	2-16-70	1	C. R. Allen, personal communication, 1970
A 10	Pallett Creek	San Andreas	2-18-70	1	C. R. Allen, personal communication, 1970
A 11	Big Pines	San Andreas	5-5-67	2	C. R. Allen, personal communication, 1970
A 12	Cajon	San Andreas	2-26-70	2	C. R. Allen, personal communication, 1970
A 13	Waterman Canyon	San Andreas	4-30-71	2	C. R. Allen, personal communication, 1970; Hileman et al., 1971
A 14	Santa Ana Wash	San Andreas	2-1-71		Hileman, et al., 1971
A 15	Colton	San Jacinto	4-29-70	1	Hileman, et al., 1971
A 16	Devers Hill	Banning	4-28-70	1	Hileman, et al., 1971
A 17	Long Canyon	Mission Creek	2-24-70	1	Hileman, et al., 1971
A 18	Lamb Canyon	San Jacinto	1-71		Hileman, et al., 1971
A 19	Casa Loma	Casa Loma	2-16-70	1	Hileman, et al., 1971
A 20	Indio Hills	San Andreas	4-16-70	1	Hileman, et al., 1971
A 21	Dillon Road	San Andreas	4-17-70	1	Hileman, et al., 1971
A 22	Red Canyon	San Andreas	5-11-67	8	Hileman, et al., 1971
A 23	Anza	San Jacinto	6-19-69	2	Hileman, et al., 1971
A 24	North Shore	San Andreas	6-20-69	3	Hileman, et al., 1971
A 25	Bertram	San Andreas	6-20-69	6	Hileman, et al., 1971
A 26	Ocotillo Wells	Coyote Creek	4-9-68	12	Hileman, et al., 1971
A 27	Baileys Well	Coyote Creek	3-31-69	3	Hileman, et al., 1971
A 28	Superstition Hills	Superstition Hills	5-7-67	9	Hileman, et al., 1971

SMALL ANGULATION ARRAYS (FAULT-CROSSING)
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Map no.	Locality	Fault	First observation	Number of observations to 1-1-71	References
A 29	Harris Road	Imperial	1-5-68	10	Hileman, *et al.*, 1971
A 30	Worthington Road	Imperial	5-10-67	11	Hileman, *et al.*, 1971
A 31	Meloland	Imperial	6-19-66	12	Hileman, *et al.*, 1971
A 32	Seeley	Landslide	4-23-68	1	Hileman, *et al.*, 1971
A 33	Dixieland	Coyote Creek	8-8-70	1	Hileman, *et al.*, 1971
A 34	All American Canal	Imperial	5-10-67	9	Hileman, *et al.*, 1971

STRAIN METERS

Map no.	Locality and site	Date installed	Agency	Instrumentation	References
S 1	Watsonville: Chase Ranch	1970	NCER	Stress probe	J. C. Savage, personal communication, 1970
S 2	Hollister: San Andreas Geophysical Observatory	1972	UCB	Quartz-rod extensometer, two-component	B. A. Bolt, personal communication, 1971
S 3	Fremont Peak	1970	NCER	Stress probe	J. C. Savage, personal communication, 1970
S 4	Paicines: Stone Canyon	1967	EML	Quartz-rod extensometer, two-component	Bufe *et al.*, 1970
S 5	Lake Isabella: Isabella	1957	CIT	Quartz-rod extensometer, two-component	Benioff, 1959
S 6	Glendora: Dalton	1953	CIT	Quartz-rod extensometer, two-component (not operating)	Benioff, 1959
S 7	Pasadena: Pasadena	1959	CIT	Quartz-rod extensometer, two-component	C. R. Allen, personal communication, 1970
S 8	Nightingale: Pinyon Flat	1970	UCSD	Laser interferometer: 800-m base; two-component	J. N. Brune, personal communication, 1971
S 9	Palomar Mountain: Palomar	1954	CIT	Quartz-rod extensometer, two-component (not operating)	C. R. Allen, personal communication, 1970
S 10	Miramar: Camp Elliot	1969	UCSD	Laser interferometer: 800-m base; one-component	J. N. Brune, personal communication, 1971

TILTMETERS AND TILT ARRAYS

Map no.	Locality and site	Date installed	Agency	Instrumentation	References
TM 1	Berkeley: Berkeley	1970	NCER	Meter, two-component mercury-tube	Wood *et al.*, 1971
TM 2	San Francisco: Presidio	1968	NCER	Meter, two-component mercury-tube	Wood *et al.*, 1971
TA 1	Milpitas: Calaveras Reservoir	1969	NCER	Array	J. C. Savage, personal communication, 1970
TM 3	Mt. Hamilton	1970	NCER	Meter, two-component mercury-tube	Wood *et al.*, 1971
TA 2	Watsonville: Chase Ranch	1969	NCER	Array	J. C. Savage, personal communication, 1970
TA 2	Watsonville: Chase Ranch	1969	NCER	Array	J. C. Savage, personal communication, 1970
TM 4	Hollister: Fremont Peak	1971	NCER	Meter, two-component mercury-tube	J. C. Savage, personal communication, 1970
TM 4	Cienega Valley: Harris Ranch	1970	UCB	Meter	B. A. Bolt, personal communication, 1971
TM 5	Paicines: Stone Canyon	1966	EML	Meter, two-component mercury-tube	Bufe *et al.*, 1970
TM 6	Cholame Valley: Gold Hill	1972	DMG	Meter, biaxial electrolytic bubble	
TM 7	Lake Isabella: Isabella	1964	CIT	Meter, two-component mercury-tube	C. R. Allen, personal communication, 1970
TM 8	Carrizo Plain: Las Yeagus Ranch	1972	DMG	Meter, biaxial electrolytic bubble	
TM 9	Carrizo Plain: Dillard Ranch	1972	DMG	Meter, biaxial electrolytic bubble	
TM 10	Taft: Buena Vista fault	1967?	NOS	Meter, two-component mercury-tube	R. D. Nason, personal communication, 1970
TA 3	Ocotillo Wells: Borrego Mountain	1969	NCER	Array	J. C. Savage, personal communication, 1970
TA 3	Ocotillo Wells: Borrego Mountain	1969	NCER	Array	J. C. Savage, personal communication, 1970
TA 3	Ocotillo Wells: Borrego Mountain	1969	NCER	Array	J. C. Savage, personal communication, 1970
TA 3	Ocotillo Wells: Borrego Mountain	1969	NCER	Array	J. C. Savage, personal communication, 1970

CREEPMETERS (C) AND ALIGNMENT ARRAYS (A)

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Map no.	Locality and site	C or A	Fault	Installation date and observation frequency	Agency	References
C 1	Manchester: Scaramella Ranch	A	San Andreas	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 2	Fort Ross: Timber Cove	A	San Andreas	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 3	Inverness: Inverness Road	A	San Andreas	1969--annual	EML	Nason, 1971
C 4	San Pablo: El Portal School	C	Hayward	1971	EML	Nason, 1971
C 4	San Pablo: San Pablo	A	Hayward	1968--semiannual	NCER	J.C. Savage, personal communication, 1970
C 5	Bolinas: Woodville	A	San Andreas	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 6	El Cerrito: Country Club Drive	A	Hayward	1968--annual	EML	Nason, 1971
C 6	Berkeley: Memorial Stadium	C	Hayward	1966	UCB	Bolt and Marion, 1966
C 7	Oakland: Rettig Street	A	Hayward	1970--annual	EML	Nason, 1971
C 7	Oakland: Holy Redeemer College	A	Hayward	1968--annual	EML	Nason, 1971
C 7	Oakland: Naval Hospital	A	Hayward	Unknown	City of Oakland	J.E. McCarty, personal communication, 1970
C 7	Oakland: MacArthur Freeway at 106th Street overcrossing	A	Hayward	Unknown	City of Oakland	J.E. McCarty, personal communication, 1970
C 7	Oakland: MacArthur Freeway at Sequoyah Road overcrossing	A	Hayward	Unknown	City of Oakland	J.E. McCarty, personal communication, 1970
C 7	Oakland: MacArthur Freeway at Keller Avenue overcrossing	A	Hayward	Unknown	City of Oakland	J.E. McCarty, personal communication, 1970
C 7	Oakland: Warren Freeway at Joaquin Miller Rd. overcrossing	A	Hayward	Unknown	City of Oakland	J.E. McCarty, personal communication, 1970
C 7	Oakland: Warren Freeway at LaSalle Avenue overcrossing	A	Hayward	Unknown	City of Oakland	J.E. McCarty, personal communication, 1970
C 7	Oakland: Warren Freeway at Broadway Terrace overcrossing	A	Hayward	Unknown	City of Oakland	J.E. McCarty, personal communication, 1970
C 8	San Leandro: Montrose Drive	A	Hayward	1969--annual	City of San Leandro/EML	Nason, 1971
C 8	San Leandro: Estudillo Road	A	Hayward	1969--annual	City of San Leandro/EML	Nason, 1971
C 8	San Leandro: Astor Drive	A	Hayward	1969--annual	City of San Leandro/EML	Nason, 1971
C 8	San Leandro: Lake Chabot	A	Hayward	1969--annual	City of San Leandro/EML	Nason, 1971

CREEPMETERS (C) AND ALIGNMENT ARRAYS (A)

Map no.	Locality and site	Fault	C or A	Installation date and observation frequency	Agency	References
C 8	San Leandro: Chabot Road	Hayward	A	1969--annual	City of San Leandro/EML	Nason, 1971
C 9	Daly City: Longview Drive	San Andreas	A	1969--annual	EML	Nason, 1971
C 10	Hayward: Grove Street	Hayward	A	1967--annual	City of Hayward/EML	Nason, 1971
C 10	Hayward: Rose Street	Hayward	C A	1968 1967--annual	City of Hayward/EML	Nason, 1971
C 10	Hayward: Sunset Boulevard	Hayward	A	1967--annual	City of Hayward/EML	Nason, 1971
C 10	Hayward: Simon Street	Hayward	A	1967--annual	City of Hayward/EML	Nason, 1971
C 10	Hayward: C Street	Hayward	A	1967--annual	City of Hayward/EML	Nason, 1971
C 10	Hayward: D Street	Hayward	C A	1968 1967--annual	City of Hayward/EML	Nason, 1971
C 10	Hayward: Doric Motel	Hayward	A	1968--annual	City of Hayward/EML	Nason, 1971
C 10	Hayward: Palisade Drive	Hayward	C A	1970 1968--annual	City of Hayward/EML	Nason, 1971
C 11	Westborough: Dunhallow	San Andreas	A	1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 11	Westborough: Meath	San Andreas	A	1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 11	Westborough: Barryrae	San Andreas	A	1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 12	San Bruno: Sneath Lane	San Andreas	A	1969--annual	EML	Nason, 1971
C 13	Fremont: Shinn Street	Hayward	C	1970	EML	Nason, 1971
C 13	Fremont: Bodily Street	Hayward	A	1968--annual	EML	Nason, 1971
C 13	Fremont: Nursery Street	Hayward	C	1971--annual	EML	Nason, 1971
C 13	Fremont: Union Street	Hayward	C	1971--annual	EML	Nason, 1971
C 13	Fremont: Osgood Street	Hayward	A	1968--annual	EML	Nason, 1971
C 14	Fremont: Fremont Prune	Hayward	A C	1968--semiannual 1969	NCER	J.C. Savage, personal communication, 1970
C 15	Woodside: Roberta Drive	San Andreas	A	1968--semiannual	NCER	J.C. Savage, personal communication, 1970
C 16	Monte Bello Ridge: Morrel Ranch	San Andreas	A	1966--semiannual	NCER	J.C. Savage, personal communication, 1970

CREEPMETERS (C) AND ALIGNMENT ARRAYS (A)

Map no.	Locality and site	Fault	C or A	Installation date and observation frequency	Agency	References
C 17	San Jose: Aborn Road	Silver Creek	A	1970--annual	EML	
C 18	Halls Valley: San Felipe	Calaveras	A	1969--semiannual	NCER	J.C. Savage, personal communication, 1970
C 19	Coyote Lake: Coyote	Calaveras	A C	1968--semiannual 1969	NCER	J.C. Savage, personal communication, 1970
C 20	San Felipe Lake: San Felipe North	Calaveras	A	1969	USBR	
C 20	San Felipe Lake	Calaveras	A	1969	USBR	
C 21	Corralitos: Green Valley Road	San Andreas	A	1970--annual	EML	Nason, 1971
C 21	Corralitos: Holy Cross	San Andreas	A	1968--annual	EML	Nason, 1971
C 22	Watsonville: Chase Ranch #1	Sargent	C A	1969 1969--annual	NCER	J.C. Savage, personal communication, 1970
C 22	Watsonville: Chase Ranch #2	Sargent	A	1969	NCER	J.C. Savage, personal communication, 1970
C 23	Watsonville: Chamberlain Ranch	San Andreas	A	1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 24	Hollister Valley: Lake Road	Calaveras	C A	1969 1967--monthly	EML	Nason, 1971
C 24	Hollister Valley: Costa	Calaveras	C	1969--semiannual	NCER	J.C. Savage, personal communication, 1970
C 24	Hollister Valley: Shore Road	Calaveras	C	1971	EML	Nason, 1971
C 24	Hollister Valley: Shore Road	Calaveras	A	1968--monthly	DMG/EML	Nason, 1971
C 24	Hollister Valley: Busch Ranch	Branch of Calaveras	C*	1970	EML	Nason, 1971
C 24	Hollister Valley: Bertuccio Ranch	Calaveras	C	1971	EML	Nason, 1971
C 24	Hollister Valley: McConnell Road	Calaveras	A	1968--monthly	DMG/EML	Nason, 1971
C 24	Hollister Valley: Wright Road	Calaveras	C	1971	EML	Nason, 1971
C 24	Hollister Valley: Wright Road	Calaveras	A	1967--monthly	DMG/EML	Nason, 1971
C 25	Hollister: Locust Avenue	Calaveras	A	1967--monthly	DMG/EML	Nason, 1971
C 25	Hollister: Central Avenue	Calaveras	C	1970	EML	Nason, 1971
C 25	Hollister: Seventh Street	Calaveras	A C	1967 1970	DMG/EML	Nason, 1971
C 25	Hollister: D Street	Calaveras	A	--monthly	DMG/EML	Nason, 1971
C 25	Hollister: D Street	Calaveras	C	1970	EML	Nason, 1971
C 25	Hollister: Nash Road	Calaveras	A	1969--monthly	DMG/EML	Nason, 1971
C 25	Hollister: Southside Road	Calaveras	A	1969--monthly	DMG/EML	Nason, 1971
C 25	Hollister: Hospital Road	Calaveras	A	1969--quarterly	DMG/EML	Nason, 1971

CREEPMETERS (C) AND ALIGNMENT ARRAYS (A)

Map no.	Locality and site	Fault	C or A	Installation date and observation frequency	Agency	References
C 26	San Juan Bautista: Old San Juan-Hollister Road	San Andreas	C A	1971 1967--annual	EML	Nason, 1971
C 26	San Juan Bautista: Nyland Ranch	San Andreas	C A	1968 1967--annual	EML	Nason, 1971
C 26	San Juan Bautista: Grant Road	San Andreas	A	1967--monthly	DMG/EML	Nason, 1971
C 26	San Juan Bautista: St. Francis Retreat	San Andreas	C	1971	EML	Nason, 1971
C 26	San Juan Bautista: St. Francis Retreat	San Andreas	A	1969--annual	DMG/EML	Nason, 1971
C 26	San Juan Bautista: St. Francis Retreat	San Andreas	A	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 27	Cienega Valley: Harris Ranch	San Andreas	A C	1964--annual 1969	NCER	J.C. Savage, personal communication, 1970
C 27	Cienega Valley: Harris Ranch	San Andreas	C	1969	UCB	B.A. Bolt, personal communication, 1970
C 28	Cienega Valley: Vineyard	San Andreas	A	1964--annual	DMG/EML	Nason, 1971
C 28	Cienega Valley: Winery	San Andreas	C A	1958 1967--annual	EML	Nason, 1971
C 29	Cienega Valley: Cienega Valley	San Andreas	A	1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 29	Paicines: Limekiln Road	San Andreas	A	1964--annual	EML	Nason, 1971
C 30	Paicines: Pescadero Creek	San Andreas	C A	1971 1969--annual	EML	Nason, 1971
C 31	Paicines: Stone Canyon	San Andreas	C C A	1968 1970 1968--annual	EML	Nason, 1971
C 32	Bear Valley: Melendy Ranch	San Andreas	C A	1969 1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 32	Bear Valley: Melendy Ranch	San Andreas	C C	1969 1970	EML	Nason, 1971
C 33	Bear Valley: River Terrace	San Andreas	A	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 34	Lone Pine: Lone Pine Aqueduct	Sierra Nevada Frontal	C	1968	EML	R.D. Nason, personal communication
C 35	San Benito: San Benito	San Andreas	C A	1969 1964--annual	EML	Nason, 1971

CREEPMETERS (C) AND ALIGNMENT ARRAYS (A)

Map no.	Locality and site	Fault	C or A	Installation date and observation frequency	Agency	References
C 36	San Benito: Dry Lake	San Andreas	C A	1969 1967--annual	NCER	J.C. Savage, personal communication, 1970
C 37	Bitterwater: Little Rabbit Valley	San Andreas	C	1969	NCER	J.C. Savage, personal communication, 1970
C 38	Bitterwater: Bitterwater	San Andreas	A	1964--annual	EML	Nason, 1971
C 38	Bitterwater: Eade Ranch	San Andreas	A	1964--annual	EML	Nason, 1971
C 38	Bitterwater: Eade Ranch	San Andreas	A	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 38	Bitterwater: Smith Ranch	San Andreas	C A	1969 1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 39	Mustang Ridge: De Alvarez Ranch	San Andreas	A	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 40	Mustang Ridge: Kenner Lake	San Andreas	A	--semiannual	NCER	J.C. Savage, personal communication, 1970
C 41	Mustang Ridge: Monarch Peak	San Andreas	C A	1969 1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 42	Mustang Ridge: Mee Ranch	San Andreas	A	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 43	Slack Canyon: Slack Canyon	San Andreas	C A	1969 1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 44	Stone Canyon: Bagsby Ranch	San Andreas	A	1970--semiannual	NCER	J.C. Savage, personal communication, 1970
C 45	Parkfield: Durham Ranch	San Andreas	C A	1969 1967--semiannual	NCER	J.C. Savage, personal communication, 1970
C 46	Parkfield: Carr Ranch	San Andreas	C	1966	CIT	Allen and Smith, 1966
C 46	Cholame Valley: Gold Hill	San Andreas	C	1969	NCER	J.C. Savage, personal communication, 1970
C 47	Cholame: Water tank	San Andreas	C A	1969 1966--semiannual	NCER	J.C. Savage, personal communication, 1970
C 48	Cholame: Junction of Highways 46 and 41	San Andreas	C A	1971 1968--annual	EML	Nason, 1971
C 49	Twisselman Ranch: Twisselman Ranch	San Andreas	C	1969	CIT	C.R. Allen, personal communication, 1970
C 50	Bakersfield: Oildale	Kern Front	C	1968	EML	R.D. Nason, personal communication, 1971
C 51	Taft: Buena Vista Hills	Buena Vista	C	1967	EML	R.D. Nason, personal communication, 1971

Map no.	Locality and site	Fault	C or A	Installation date and observation frequency	Agency	References
C 52	Pilot Knob Valley: Randsburg Test Range	Garlock	A	1969--semiannual	NCER	J.C. Savage, personal communication, 1971
C 53	Mojave Desert: Manix	Manix	C A	1970 1967--quarterly	SDSC	A. Bassett, personal communication, 1971
C 54	Santa Cruz Island: Stanton Ranch	Santa Cruz Island	A	1969	UCSB	A. Sylvester, personal communication, 1971
C 55	Salton Sea: North Shore	San Andreas	C	1970	CIT	C.R. Allen, personal communication, 1970
C 56	Ocotillo Wells: Borrego Mountain	Coyote Creek	A	1968--semiannual	NCER	J.C. Savage, personal communication, 1970
C 57	Ocotillo Wells: Ocotillo Wells	Coyote Creek	C	1968	EML	R.D. Nason, personal communication, 1971
C 58	Ocotillo Wells: Lower Borrego Valley	Coyote Creek	A	1969--semiannual	NCER	J.C. Savage, personal communication, 1970
C 59	Fish Creek Mountains	Superstition Hills	A	1969--semiannual	NCER	J.C. Savage, personal communication, 1970
C 60	Superstition Hills	Superstition Hills	C	1967	CIT	C.R. Allen, personal communication, 1970

KEY TO AGENCY ABBREVIATIONS

CIT. . . . . California Institute of Technology
DMG. . . . . California Division of Mines and Geology
DWR. . . . . California Department of Water Resources
EML. . . . . Earthquake Mechanism Laboratory NOAA
IC . . . . . Imperial College, London, United Kingdom
NCER . . . . National Center for Earthquake Research USGS
NOS. . . . . National Ocean Survey NOAA

SDSC . . . . San Diego State College
TJC. . . . . Taft Junior College
UCB. . . . . University of California, Berkeley
UCR. . . . . University of California, Riverside
UCSB . . . . University of California, Santa Barbara
UCSD . . . . University of California, San Diego
USBR . . . . U.S. Bureau of Reclamation

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